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Bezeichnung: Method of electroplating a workpiece having high-aspect ratio holes

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Method of electroplating a workpiece having high-aspect ratio holes

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Method of electroplating a workpiece having high-aspect ratio holes

Specification:

The production of high-aspect ratio printed circuit boards, for example so-called back panels, poses well-known problems for good quality electrolytic copper metallization. The panels can be from 3 mm and up to 10 mm thick with aspect ratios of typically 10 : 1. However, there is a current trend requiring even thicker panels and with an aspect ratio up to 15 : 1. Such panels typically can be larger than "normal" production panels which gives added problems in handling due to their weight. One of the limiting factors in copper deposition is the mass transport of ions into the high-aspect ratio holes. Achieving the required copper thickness in the hole without over-plating the surface causing resist over-plating with pattern plate or poor line definition with panel plate are the main problems in the production of high-aspect ratio panels. A further factor with back panels is the difficulty of component mounting using the press-fit technique when the copper deposit distribution is poor. To overcome throwing power problems low electroplating current densities have been used which obviously have a negative impact on productivity. As a solution to these problems reverse pulse plating can allow the use of higher current densities with improved surface distribution and throwing power in the through-holes as described in DE 42 25 961 C2 and DE 27 39 427 A1.

In horizontal processing of printed circuit boards it has emerged that the high-aspect ratio throwing power in Uniplate® (Atotech Deutschland GmbH) systems has been a restriction to their use for the production of thicker panels. Even for panels thicker than 1.6 mm the copper throwing power has not been fully acceptable depending on the aspect ratio. The reasons for this have been because of the emphasis on the production of thinner material at higher current densities with blind micro-vias. The high-current density, in the order of 10 A/dm² average and the requirement to produce blind micro-vias under such conditions has required the use of relatively high-copper concentrations at

above 35 g/l. Both of these factors have not enabled the best throwing power in high-aspect ratio panels. Trials have been made to improve the throwing power in standard Inpulse® (Atotech Deutschland GmbH) equipment. But these have only given a marginal improvement. These trials were limited by the pulse parameters which are available with the standard Inpulse® system.

Up to now in reverse pulse plating printed circuit boards, duration of forward pulses has been set to 10 – 80 ms, and duration of reverse pulses has been set to 0.5 – 6 ms. This has resulted in a frequency range of from about 12 to about 95 Hz. If printed circuit boards have been to be produced which were 2 mm thick and which contained through holes with an aspect ratio of 10 : 1 acceptable throwing power of copper deposition in the through holes has been achieved at a current density in the range of 1 – 10 A/dm^2 for the forward pulses and at a current density in the range of 10 – 40 A/dm^2 for the reverse pulses. If printed circuit boards with a thickness of greater than 2 mm have been to be produced, the current densities must be decreased in order to achieve an acceptable result in throwing power.

In a joint project with the Kurt-Schwabe-Institut für Mess- und Sensortechnik e.V., Germany, the flow dynamics of copper deposition was investigated. The results from this investigation has been published by Reents, B., Thies, A., Langheinrich, P.: "Online measurement of flow and mass transfer in micro-holes with PIV and an electrochemical sensor array". Proc. ISE Symp., 2002, Düsseldorf, Germany. The influences on copper deposition in blind micro-vias have been documented as part of these experiments and have been published by Reents, B., Kenny, S.: "The influence of fluid dynamics on plating electrolyte for the successful production of blind micro-vias". IPC Expo 2002 Proc. of the Techn. Conf. IPC, Northbrook, Ill., USA (2002).

From the above it is apparent that a main problem in electroplating printed circuit boards with high-aspect ratio through holes is to achieve a sufficient metal plating thickness in the hole. At the same time it is mandatory to run electroplating at a minimum average current density at the printed circuit board in order to ensure adequate efficiency of the process which may only be

garantueed if the through-put and hence plating current density is high-enough. Finally also good surface quality must be ensured which means that the metal deposit produced must be as even and shiny as possible.

The object of the present invention is therefore to fulfill the above requirements and more specifically to achieve sufficient metal plating thickness in high-aspect ratio printed circuit boards. Another object of the present invention is also to ensure that electroplating efficiency is as high as possible which implies that metal plating current density at the printed circuit boards must be as high as possible. A suitable average plating current density is held to be at least 3 A/dm².

These problems are solved by the method of electroplating a workpiece comprising high-aspect ratio holes according to claim 1. Preferred embodiments of the invention are outlined in the subordinate claims.

The method according to the present invention serves to electroplate a workpiece having high-aspect ratio holes. The method comprises the following method steps:

a. The workpiece is brought into contact with a metal plating electrolyte.
b. A voltage is applied between the workpiece and at least one anode, to the effect that a current flow is provided to the workpiece. The current flow generated is a pulse reverse current flow. The pulse reverse current has a frequency of at most 6 Hertz. In each cycle time of the pulse reverse current at least one forward current pulse and at least one reverse current pulse are provided.

In a preferred embodiment the ratio of the duration of the at least one forward current pulse to the duration of the at least one reverse current pulse is set to at least 5, more preferably to at least 15 and still more preferably to at least 18. This ratio may be set to at most 75 and more preferably to at most 50. The ratio may most preferably be set to about 20.

The duration of the at least one forward current pulse may preferably be set to at least 100 ms, more preferably to at least 160 ms and most preferably to at least 240 ms.

The duration of the at least one reverse current pulse may preferably be set to at least 0.5 ms, more preferably to at least 8 ms and most preferably to at least 12 ms.

The peak current density at the workpiece of the at least one forward current pulse may be set to at least 3 A/dm². It may be set to at most 15 A/dm². Most preferably the peak current density at the workpiece of the at least one forward current pulse may be about 5.5 A/dm².

The peak current density at the workpiece of the at least one reverse current pulse may especially be set to at least 10 A/dm². It may be set to at most 60 A/dm². Most preferably the peak current density at the workpiece of the at least one reverse current pulse may be in the range of from about 16 to about 20 A/dm².

In a preferred embodiment of the present invention the rise times of the forward and reverse current pulses, respectively, may be adjusted depending on the technical objective pursued.

The workpiece is preferably plate-shaped. It may more preferably be a printed circuit board or any other plate-shaped electrical circuit carrier, such as a semiconductor wafer (integrated circuit) or any hybrid (IC-) chip carrier like a multi-chip module.

In a preferred embodiment of the present invention the method comprises the following method steps:

a. A first voltage is applied to between a first side of the workpiece and at least one first anode, to the effect that a first pulse reverse current flow is provided to the first side of the workpiece, said first pulse reverse current

flow having at least one first forward current pulse and at least one first reverse current pulse flowing in each cycle time.

b. A second voltage is applied to between a second side of the workpiece and at least one second anode, to the effect that a second pulse reverse current flow is provided to the second side of the workpiece, said second pulse reverse current flow having at least one second forward current pulse and at least one second reverse current pulse flowing in each cycle time.

As to this last embodiment the at least one first forward and reverse current pulses may be offset relative to the at least one second forward and reverse current pulses, respectively. In a more preferred embodiment of the present invention this offset between the first current pulses and the second current pulses is approximately 180°.

For further improving throwing power the current flow may comprise, in each cycle time, two forward current pulses with one zero current break between the two forward current pulses and one reverse current pulse.

Further in the course of metal plating the workpiece, at least one parameter of the pulse reverse current flow, selected from the group comprising the ratio of the duration of the forward current pulse to the duration of the reverse current pulse and the ratio of the peak current density of the forward current pulse to the peak current density of the reverse current pulse, may be varied. More specifically it turns out to be advantageous to increase, in the course of metal plating the workpiece, the ratio of the peak current density of the forward current pulse to the peak current density of the reverse current pulse and/or to decrease the ratio of the duration of the forward current pulse to the duration of the reverse current pulse.

Another improvement of the invention comprises bringing the workpiece into contact with the metal plating electrolyte by delivering the metal plating electrolyte towards the surface of the workpiece at an electrolyte flow velocity relative to the surface of the workpiece. The metal plating electrolyte is

preferably forced under agitation towards the workpiece. More preferably the electrolyte flow velocity at the surface of the workpiece comprises a velocity component normal to the surface of the workpiece being at least 1 m/sec.

In a further improvement of the present invention the method comprises providing at least one anode being inert and dimensionally stable.

According to one specific embodiment of the present invention the metal plating electrolyte may be a copper plating electrolyte.

In this latter case, and especially if the at least one anode is inert and dimenstionally stable, copper may be replenished to the electrolyte by dissolving copper metal. For this purpose the copper plating electrolyte may contain at least one compound capable of oxidizing copper metal to copper ions. Such oxidizing compound may be for example a ferric compound, such as ferric ion, ferric sulphate more specifically. As an alternative this oxidizing compound may also be oxygen, which may preferably be generated in the electrolyte by dissolution of oxygen from the air.

Now, referring to the investigations outlined above, further experiments have been carried out to investigate the influences on through-hole plating, particularly in high-aspect ratio holes. Table 1 gives a summary of electrolyte exchange mechanism considered and also the influencing factors.

The influencing parameters were held constant as far as possible, and the artificial convection by means of forced flooding was investigated.

A specially designed multilayer printed circuit board with electrochemical flow sensor was used as part of these investigations. A schematic of one test hole on the test board is shown in fig. 1. This test board comprises a micro electrode array.

The test board was placed in a test chamber which allowed the variation of key parameters as follows:

- Diameter of nozzle
- Angle α between beam of fluid and workpiece surface
- Distance between nozzle mouth and workpiece surface
- Lateral flow along the surface of the workpiece
- Pressure / Flow
- Density of the electrolyte
- Pulse pumping

The test chamber is shown in fig. 2. This test chamber is being used for hydrodynamic studies. The test chamber comprises a housing 1, which emcompasses an adjustable disc 2. On this disc 2 the test printed circuit board 3 is arranged in a vertical arrangement. The item with numeral 4 is a stopper. The electrochemical cell also comprises a counter electrode 5 and a reference electrode 6, which both are also schematically displayed in fig. 1. A nozzle 7 serves to impinge metal plating electrolyte to the surface of the printed circuit board 5 at an angle α which is defined as the angle between the axis of the nozzle 7 and the upper right hand part of the test printed circuit board 3 as shown in this fig. Finally there is a lateral nozzle adjustment means 8 which allows fine tuning of the point of impingement of the metal plating electrolyte at the test printed circuit board.

Fig. 3 shows a microsection through one test coupon having a hole with a diameter of 0.2 mm showing the inner layer electrode connections, the results from experiments with this test coupon being given in fig. 4. This fig. illustrates the results of investigation of fluid velocity and spray angle α as a function of current I at the individual inner layer electrodes. The experiments have been carried out under the following conditions:

Ring electrodes being formed in the inner layer of the test coupon circular to the hole with d = 200 µm;
The aspect ratios of the holes contained in the test coupons being:
in fig. 4.A: 1.3 (upstream);
in fig. 4.B: 2.8 (middle);

in fig. 4.C: 4.4 (downstream);
The aspect ratio was calculated in each individual case as the ratio of the distance from the hole entry to the respective inner layer, which was located upstream of the middle of the hole, in the middle of the hole and downstream the middle of the hole, respectively, to the hole diameter.
L_x = - 0.2 mm

Fluid flow velocity $v_j(y)$ was as follows:

1) 0.66 m/sec
2) 1.46 m/sec
3) 3.7 m/sec
4) 7,2 m/sec
5) 11.5 m/sec

The curves in the diagrams in fig. 4 are designated with numerals 1, 2, 3, 4 and 5 to correspond to the above fluid flow velocities $v_j(y)$. The results show that a maximum diffusion current is achieved at a flow angle of 90° and of course with the highest impingement velocity.

In larger scale tests the technique of particle image velocimetry (PIV) was used to image the flow of electrolyte through a high-aspect ratio panel. Fig. 5 shows the experimental set-up (particle image velocimetry apparatus) used to carry out the tests. In this a dynamic system is illuminated by two laser beams, and the resulting interference pattern information is recorded on a camera.

The data obtained from one of the flow experiments through a high-aspect ratio panel are shown in fig. 6, which is an illustration of vertical solution flow through a high-aspect ratio panel. The individual arrows show the direction and size of velocity vectors at the respective locations in the examined area.

The results from the experiments have enabled modifications to made to the Uniplate® Inpulse® system to improve the production of blind micro-vias as reported.

Horizontal Application:

The standard Inpulse® module for horizontal processing of printed circuit boards (in which boards are conveyed in a horizontal path and in a horizontal plane of transport for processing same) has a spray bar to cathode (workpiece) separation of 95 mm and an anode to cathode separation of 75 mm. In the Inpulse® 2 both the spray bar and the anode are set much closer to the cathode at 15 mm and 8 mm for the anode. This enables a more intense electrolyte flow towards the panel and also has an added advantage making the use of anode shielding unnecessary whilst retaining excellent surface distribution. Also the spray system itself has been modified to give a more directed agitation towards the panel. These changes were made primarily to enable the more efficient flooding of blind micro-vias. Using this system experiments were made to investigate the optimal electrolyte composition and pulse plating parameters to achieve best throwing power in 3.2 mm thick panels with aspect ratio 10 : 1. The results have shown that primarily the pulse wave form set-up and the electrolyte adjustment are critical in giving throwing power improvement. The best electrolyte composition was found to be as follows:

Copper: 20 g/l
Sulphuric acid: 270 g/l
Chloride ions: 40 mg/l
Iron(II): 7 g/l
Iron(III): 1 g/l
Leveller Inpulse® H6: 1.7 – 2.0 ml/l
Brightener Inpulse®: 4.0 – 5.5 ml/l

Of course the metal plating electrolyte may vary to some extent. Throwing power may be efficiently improved if the electrical conductivity of the metal plating electrolyte is increased. This may be affected by increasing the acid concentration for example. The additive concentrations are more typical of

electrolytes adjusted to produce high-aspect ratio panels. In particular the copper concentration is 15 – 20 g/l lower than in a standard Inpulse® electrolyte.

The pulse plating parameters were varied from DC plating conditions at 4/dm² to pulse plating with forwards 250 ms and reverse 25 ms. A selection of the parameters used together with the throwing power achieved is shown in Table 2.

Due to the weakness of corner flattening by means of high-reverse conditions and surface roughness, the best throwing power results were achieved with forwards 240 ms at an average current density of 4 A/dm² and reverse of 10 ms at a current density of 16 A/dm² and not with 25 ms in reverse time. A general tendency can be seen that with lower frequency the throwing power is increased, as is clearly illustrated in Table 3.

In all tests a phase shift in pulse parameter of 180° was used. This means that the reverse pulse was applied to the anodes on one side of the test panel at the same time that the forward pulse was applied to the anodes on the other side. The pulse wave form schematic in fig. 7 (current as a function of time) illustrates this setting showing phase shift between top and bottom anodes (top curve: current at the top side of the cathode, bottom curve: current at the bottom side of the cathode).

Microsection photographs of the panel produced in test 6 outlined in Table 2 are shown in fig. 8. In this case a 10 : 1 aspect ratio panel with thickness of 3.0 mm and hole diameter of 0.3 mm was electroplated. As can be seen at the centre of the hole the thickness achieved is very low, the panel plate with the Inpulse® 2 system has a throwing power of approx. 70%.

As a comparison with similar panels, a throwing power of only 30 % would be achieved at 3 A/dm² with horizontal DC. At 2 A/dm² a throwing power of 55 % is achieved under vertical conditions in DC. Only with pulse plating under standard vertical conditions with air agitation a throwing power of 90 % is achieved, but this is at a current density of 2 A/dm². Using forced agitation improved throwing

power is possible as discussed hereinbelow. But even this is not at such a high-current density.

Vertical Application:

In vertical plating of workpieces metal plating electrolytes may be employed which have the same composition as the metal plating electrolytes described above for horizontal processing. Likewise in vertical plating pulse plating may be performed under the same conditions as in horizontal processing. Therefore as to these plating conditions in vertical plating reference is made to the above description.

In vertical systems electrolyte agitation is usually made with a combination of air agitation in the electrolyte itself and a mechanical agitation of the circuit board being plated. This mechanical agitation must ensure that the panels are moved evenly and remain vertical in the electrolyte. Otherwise solution flow will not be uniform through all the holes in the panel. To ensure this cathode movement, systems are used which clamp the panel securely and which are also used to supply current to the panel. These agitation systems, air in the electrolyte and movement of the panel, can lead to uneven fluid transport due to non-defined air agitation and due to the movement of the panel through the agitation bubbles.

To overcome these problems the use of Eductors (spray nozzles which use the Venturi Principle, *i.e.* drawing of additional liquid through the nozzle is affected by the spray created, so that high-volume flow is achieved) is becoming more common. Eductors using the Venturi Principle allow small pumps to circulate larger volumes of liquid. The kinetic energy of one solution will cause the flow of another. Typically the use of Eductors can give a 4 – 6 times increase in volume of solution movement when compared to the volume pumped. This increased volume is however at a lower pressure than the directly pumped solution. Fig. 9 shows two sizes of commonly used Eductors in electrolytic copper plating systems. The smaller Eductor shown will pump a lower volume, but will allow more Eductors to be placed on one pipe, so giving a more even electrolyte flow.

Currently the method of installation of the Eductors in a vertical plating tank is on the floor underneath the cathode as shown in fig. 10, which shows the installation of Eductors in a vertical Inpulse® line in a view from the top of the installation to the bottom. At the bottom the Eductors 9 are disposed on a feeding pipe 10.

This installation is with two pipes placed one on each side below the cathode with the Eductors adjustable pointing upwards towards or away from the cathode. There are similar installations with the Eductors mounted on a single pipe running directly below the cathode, the Eductors mounted at a fixed angle pointing alternately away from the panel. The disadvantages associated with this set-up are that the electrolyte flow uniformity depends on the positioning of the Eductors and also of the distance between the nozzle and the panel.

To give more uniform flow the Eductors can be positioned between the anodes in the plating cell pointing directly towards the cathode. This set-up has the advantage of giving a more direct flow of electrolyte towards the panel and is shown in fig. 11 as a view from the top of the installation to the side thereof. The Eductors 9 are shown to be disposed at the sides of the tank in front of the anodes 11. The disadvantage of all Eductor installations is that the solution flow can never be completely uniform over the panel surface. A compromise must be made between the number of Eductors installed and flow uniformity.

To overcome the limitations of flow uniformity by the use of Eductors a moving spray system has been developed and is being tested in a trial tank in laboratory conditions. The system consists of a spray head which moves regularly over the surface of the cathode and produces an intensive forced flooding of the panel and the through holes at the point of spraying. The head moves in a plane between anode and cathode and delivers the electrolyte in the direction towards the panel. It is so dimensioned that it does not interfere with the electrodeposition process. Initial results with high-aspect ratio panels have shown a significant improvement in throwing power when compared to standard air agitation and a more uniform deposit in comparison to Eductor agitated

equipment on the same scale. Fig. 12 shows plating results from a 3.0 mm panel with a 0.3 mm hole (aspect ratio: 10 : 1) using the moveable spray system. Average current density for electroplating was 2 A/dm². Throwing power was found to be 90 – 95 %. Reinforcement plating was performed by DC plating in horizontal plating equipment at a current density of 5 A/dm².

Investigations have been continued in the use of so-called batch plating parameters to improve throwing power, particularly in panels thicker than 5 mm. During the plating cycle the pulse parameters are varied. Normally at the start of the cycle a strong reverse charge is used to give a good throwing power followed by a lower reverse charge at the end of the plating cycle to give good surface finish. An example of such a plating sequence is given in Table 4.

Fig. 13 shows plating results from a 5.0 mm panel with a 0.5 mm hole (aspect ratio 10 : 1) using a modified pulse plating sequence together with the moveable spray system to give optimal electrolyte exchange. The average current density applied is 1.7 A/dm². The throwing power was found to be 95 – 100 %.

Use of both optimized pulse parameters as well as electrolyte agitation gives significant improvements in throwing power in trial line experiments.

Hence experiments in basic electrochemistry have shown a strong influence of electrolyte agitation on copper electroplating characteristics. Modifications to horizontal Inpulse® equipment together with optimized plating parameters show improved throwing power under experimental conditions.

In vertical equipment use of Eductors to improve agitation is becoming a standard for new equipment. However, implementation of agitation systems to give as good an agitation in vertical systems as in horizontal has not yet been achieved. The use of a moving spray flood system shows advantages in the trial line scale.

Use of varying pulse parameters over the copper deposition time have shown the possibility to improve throwing power with aggressive parameters whilst

retaining optimal surface finish using milder pulse parameters at the end of the processing time (cycle time).

Table 1: Electrolyte exchange mechanisms and influencing factors

Electrolyte exchange by	Influencing factors
• Diffusion • Migration • Natural Convection • Artificial Convection	• Concentration • Temperature • Surface Tension • Viscosity • Density

Table 2: Test conditions for Inpulse® 2 trials for 3.2 mm thick panels

Test	I average / I reverse in A/dm²	Pulse Parameters in ms Forward / Reverse	Phase Shift in °	Pulse Rise Time Factor	Surface Finish	Throwing Power min. in %
1	4 DC	DC	-	-	Good	32
2	4 / 4	240 / 20	180	1.2	Good	53
3	4 / 16	80 / 4	180	1.2	Good	49
4	4 / 16	80 / 6	180	1.2	Rough	55
5	4 / 16	250 /25	180	1.2	Rough	54
6	4 /16	240 /12	180	1.2	Good	71

Table 3: Test conditions for Inpulse® 2 trials for 3.2 mm thick panels, 0.3 mm holes, I average = 4 A/dm²

Test	I forward / I reverse in A/dm²	Pulse Parameters in ms Forward / Reverse	Phase Shift in °	Pulse Rise Time Factor	Frequency in Hz	Throwing Power min. in %
1	5.3 / 16	DC	-	-	-	30
2	5.3 /16	40 / 2	180	1.2	23.8	40
3	5.3 /16	80 / 4	180	1.2	11.9	50
4	5.3 /16	160 / 8	180	1.2	6.0	60
5	5.3 /16	240 / 12	180	1.2	4.0	70

Table 4: Pulse plating bath sequence for thick panel trials

Sequence	Exposure time mins.	A/dm² Ratio Forward to Reverse	Pulse timing ms
1	100	1 : 3	30 : 1.5
2	15	1 : 2.5	20 : 1
3	5	1 : 1.1	20 : 1

Claims:

1. Method of electroplating a workpiece comprising high-aspect ratio holes, the method comprising:

    a. bringing the workpiece into contact with a metal plating electrolyte, and
    b. applying a voltage between the workpiece and at least one anode, to the effect that a current flow is provided to the workpiece, wherein the current flow is a pulse reverse current flow having a frequency of at most 6 Hertz with, in each cycle time, at least one forward current pulse and at least one reverse current pulse.

2. Method according to claim 1, comprising setting the ratio of the duration of the at least one forward current pulse to the duration of the at least one reverse current pulse to at least 5.

3. Method according to any one of the preceding claims, comprising setting the ratio of the duration of the at least one forward current pulse to the duration of the at least one reverse current pulse to at most 75.

4. Method according to any one of the preceding claims, comprising setting the ratio of the duration of the at least one forward current pulse to the duration of the at least one reverse current pulse to about 20.

5. Method according to any one of the preceding claims, comprising setting the duration of the at least one forward current pulse to at least 100 ms.

6. Method according to any one of the preceding claims, comprising setting the duration of the at least one reverse current pulse to at least 0.5 ms.

7. Method according to any one of the preceding claims, comprising setting the peak current density of the at least one forward current pulse at the workpiece to at least 3 A/dm^2.

8. Method according to any one of the preceding claims, comprising setting the peak current density of the at least one forward current pulse at the workpiece to at most 15 A/dm².

9. Method according to any one of the preceding claims, comprising setting the peak current density of the at least one reverse current pulse at the workpiece to at least 10 A/dm².

10. Method according to any one of the preceding claims, comprising setting the peak current density of the at least one reverse current pulse at the workpiece to at most 60 A/dm².

11. Method according to any one of the preceding claims, comprising adjusting the rise times of the forward and reverse current pulses, respectively.

12. Method according to any one of the preceding claims, wherein the workpiece is plate-shaped.

13. Method according to any one of the preceding claims, wherein the workpiece is a printed circuit board or any other plate-shaped electrical circuit carrier.

14. Method according to any one of claims 12 and 13, comprising

    a. applying a first voltage to between a first side of the workpiece and at least one first anode, to the effect that a first pulse reverse current flow is provided to the first side of the workpiece, said first pulse reverse current flow having at least one first forward current pulse and at least one first reverse current pulse flowing in each cycle time, and
    b. applying a second voltage to between a second side of the workpiece and at least one second anode, to the effect that a second pulse reverse current flow is provided to the second side of the workpiece,

said second pulse reverse current flow having at least one second forward current pulse and at least one second reverse current pulse flowing in each cycle time.

15. Method according to claim 14, comprising offsetting the at least one first forward and reverse current pulses relative to the at least one second forward and reverse current pulses, respectively.

16. Method according to claim 15, comprising offsetting the first current pulses relative to the second current pulses by approximately 180°.

17. Method according to any one of the preceding claims, comprising providing the current flow, in each cycle time, with two forward current pulses with one zero current break between the two forward current pulses and one reverse current pulse.

18. Method according to any one of the preceding claims, comprising varying, in the course of metal plating the workpiece, at least one parameter of the pulse reverse current flow, selected from the group comprising the ratio of the duration of the forward current pulse to the duration of the reverse current pulse and the ratio of the peak current density of the forward current pulse to the peak current density of the reverse current pulse.

19. Method according to claim 18, comprising increasing, in the course of metal plating the workpiece, the ratio of the peak current density of the forward current pulse to the peak current density of the reverse current pulse.

20. Method according to any one of claims 18 and 19, comprising decreasing, in the course of metal plating the workpiece, the ratio of the duration of the forward current pulse to the duration of the reverse current pulse.

21. Method according to any one of the preceding claims, comprising bringing the workpiece into contact with the metal plating electrolyte by delivering the

metal plating electrolyte towards the surface of the workpiece at an electrolyte flow velocity relative to the surface of the workpiece.

22. Method according to claim 21, comprising forcing the metal plating electrolyte under agitation towards the workpiece.

23. Method according to any one of claims 21 and 22, wherein the electrolyte flow velocity at the surface of the workpiece comprises a velocity component normal to the surface of the workpiece being at least 1 m/sec.

24. Method according to any one of the preceding claims, comprising providing at least one inert and dimensionally stable anode.

25. Method according to any one of the preceding claims, wherein the metal plating electrolyte is a copper plating electrolyte.

26. Method according to claim 25, wherein the copper plating electrolyte contains at least one compound capable of oxidizing copper metal to copper ions.

27. Method according to claim 26, wherein the at least one compound capable of oxidizing copper metal to copper ion is a ferric compound.

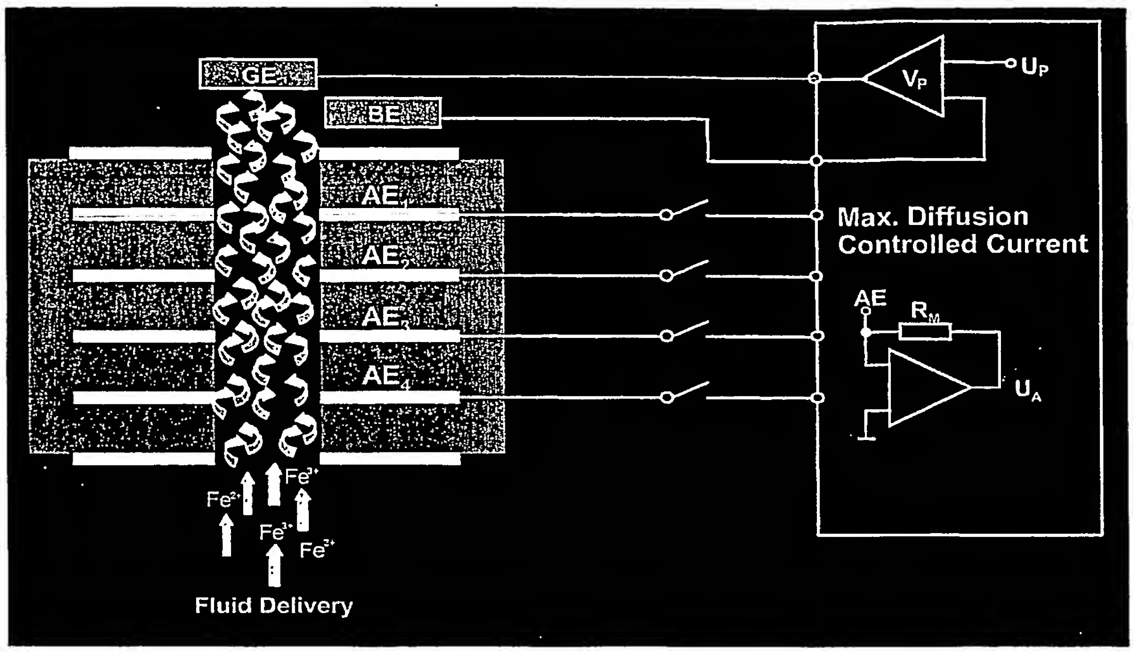
GE
BE
AE1
AE2
AE3
AE4
VP
UP
Max. Diffusion
Controlled Current
AE
RM
UA
Fe2+
Fe3+
Fe3+
Fe2+
Fluid Delivery

Fig. 1

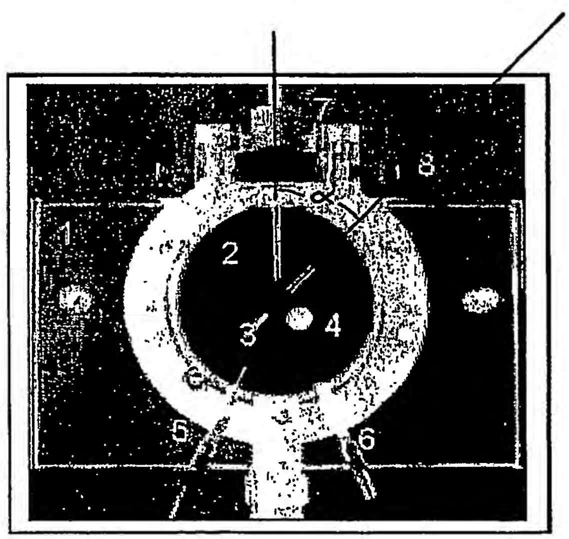
1
2
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Fig. 2

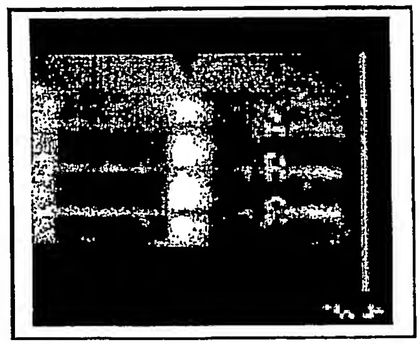

Fig. 3

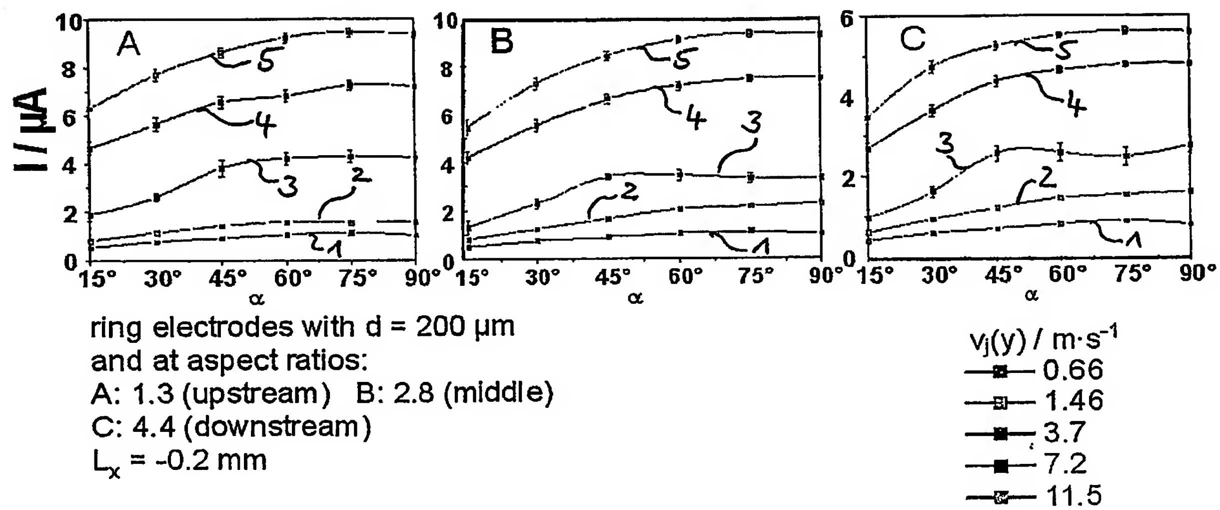
A
B
C
I / µA
α
15° 30° 45° 60° 75° 90°
1
2
3
4
5
ring electrodes with d = 200 µm
and at aspect ratios:
A: 1.3 (upstream) B: 2.8 (middle)
C: 4.4 (downstream)
L_x = -0.2 mm
$v_j(y)$ / $m \cdot s^{-1}$
0.66
1.46
3.7
7.2
11.5

Fig. 4

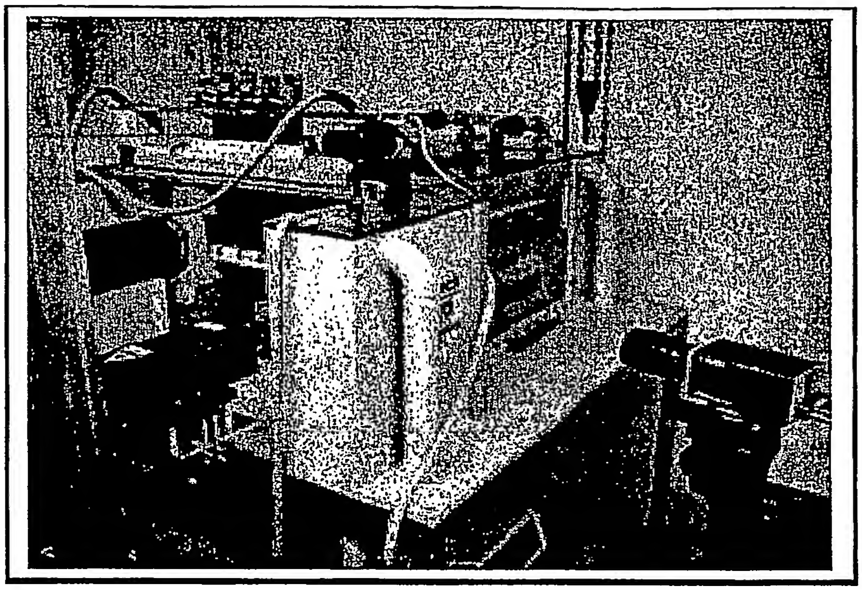

Fig. 5

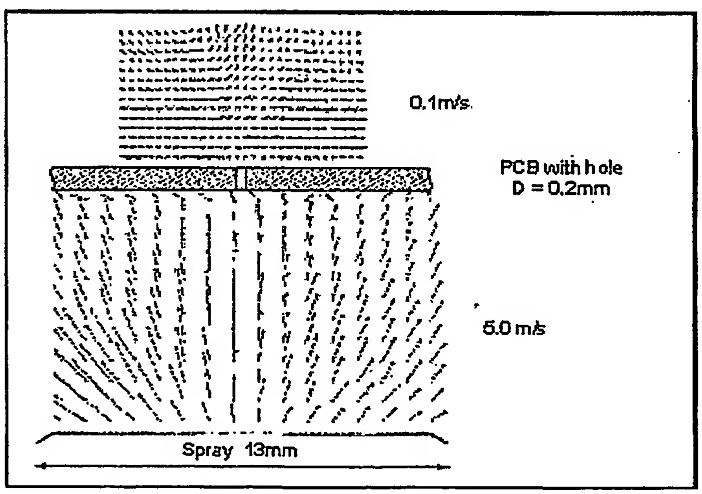

Fig. 6

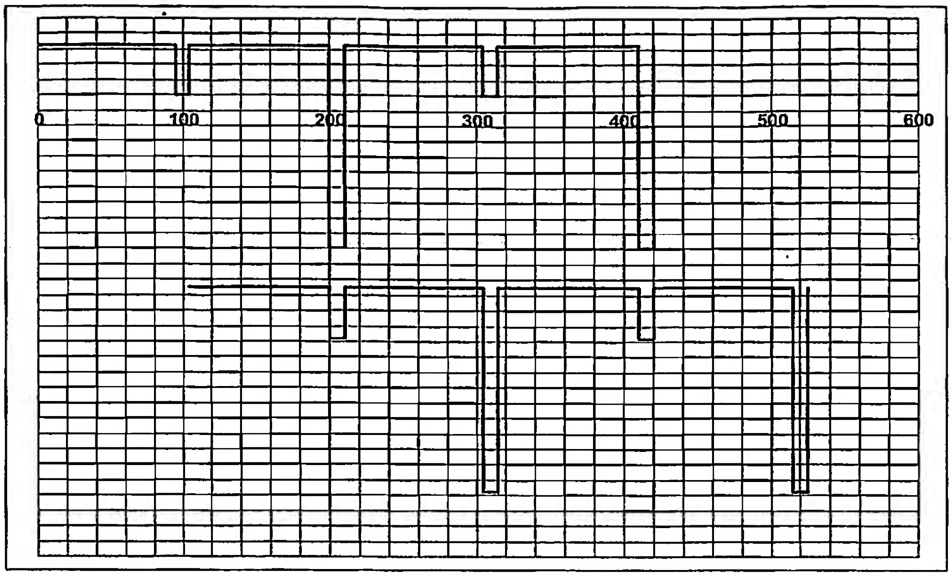

Fig. 7

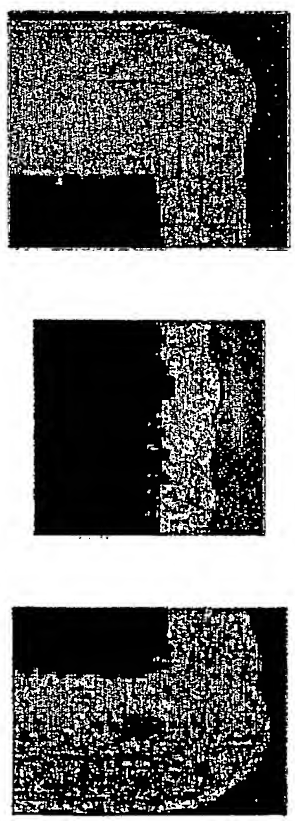

Fig. 8

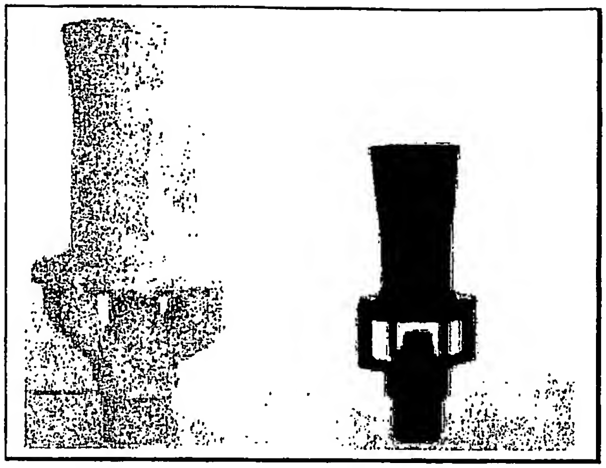

Fig.- 9

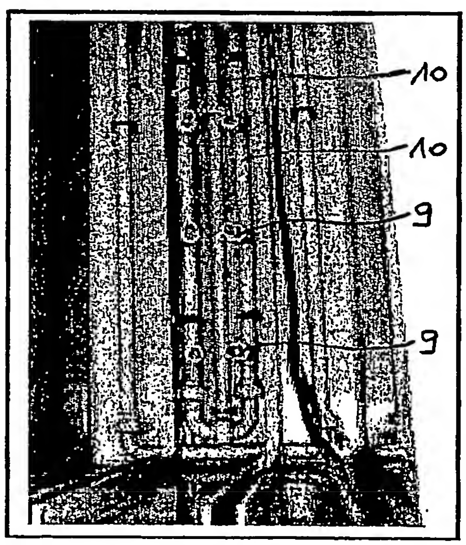

Fig. 10

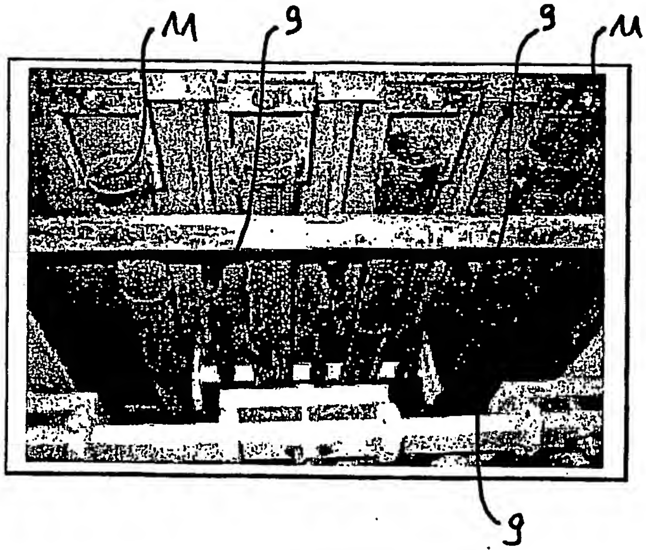

Fig. 11

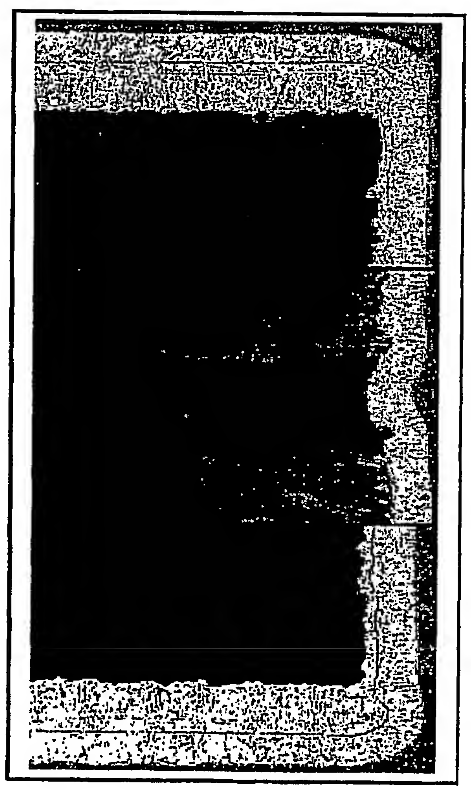

Fig. 12

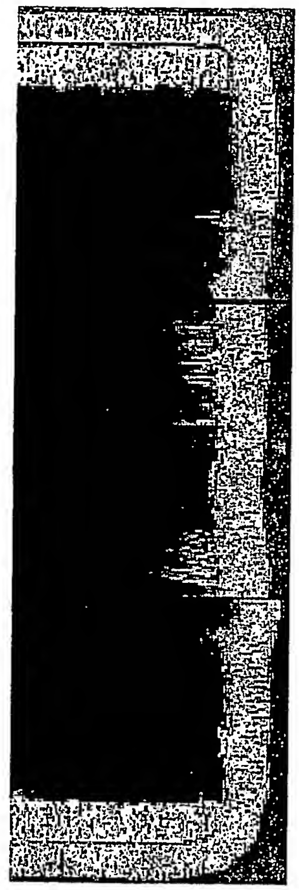

Fig. 13